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Vectorial Analysis of Dielectric Photonic Crystal VCSEL

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ABSTRACT

A new vertical-cavity surface-emitting laser structure employing a dielectric photonic crystal mirror has been suggested and been numerically investigated. The new structure has a smaller threshold gain, a moderate strength of single-transverse-mode operation, a high quality of emission beam free from the scattering, and a potential of considerably increasing the single-mode output power.

Keywords: single-mode, high power.

1. INTRODUCTION

Single-transverse-mode operation, high output power, and polarization stability of vertical-cavity surface-emitting lasers (VCSELs) are of high importance for applications of high-performance optical communication. Employing photonic crystal (PhC) in a top distributed Bragg reflector (DBR) of VCSEL for transverse confinement is one of promising approaches to potentially achieve all these features [1]-[7]. Many investigations have been performed to understand the fundamental physics and to find optimal designs of PhC VCSELs. However, large optical loss due to deeply-etched air holes still remains as a problem. The large optical loss is undesirable because it increases not only threshold current but also operating current level. High operating current can limit maximum single-mode output power via heating problem and lead to higher electrical power consumption.

In this paper, a PhC VCSEL structure based on a dielectric mirror is suggested to considerably reduce optical loss without any expense of single-mode property. It is discussed that the good single

2. DEVICE STRUCTURE AND SIMULATION METHOD

2.1 Device Structure

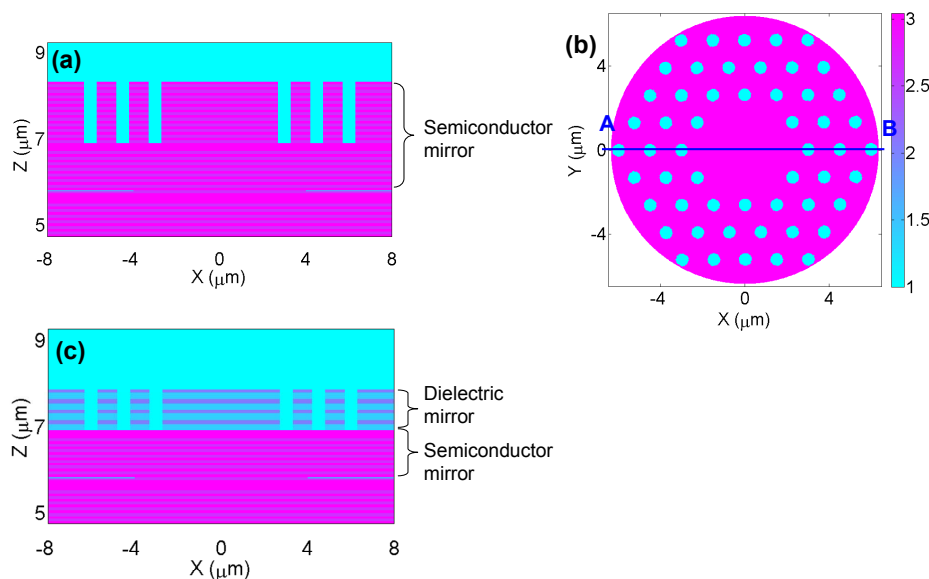


Figure 1. (a) Cross-sectional and (b) top views of the refractive index profile of the investigated semiconductor PhC VCSEL. (c) Cross-sectional refractive index profile of the dielectric PhC VCSEL.

Two PhC VCSEL structures and a reference plain VCSEL structure are investigated. In the structure of Fig. 1(a), hereafter called 'semiconductor PhC VCSEL', the top DBR is composed of 19 pairs of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ layers. Triangular-lattice air holes with $1.5\text{ }\mu\text{m}$ lattice constant and 600 nm hole diameter are formed in the upper 11 pairs. Seven air holes are missed off the center to make a defect region, as shown in Fig. 1(b). The reflectivity of un-patterned top DBR (19 pairs) is 99.63%. In the structure of Fig. 1(c), hereafter called 'dielectric PhC VCSEL', the top DBR is made of 4 pairs of $\text{TiO}_2/\text{SiO}_2$ layers and 8 pairs of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ layers. Its un-patterned reflectivity is 99.69%. Same air holes as in semiconductor PhC VCSEL are formed only in $\text{TiO}_2/\text{SiO}_2$ layers. In both devices, the active region has three 7 nm thick $\text{GaAs}/\text{AlGaAs}$ QWs in a $1\text{-}\lambda$ -cavity, the bottom DBR consists of 40 pairs of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ layers,

and an 8 μm diameter oxide aperture is situated near a node position of longitudinal standing wave. Thus, the mode confinement is mainly determined by the PhC air holes. The resonance wavelength is about 850 nm.

2.2 Simulation Method

A 3D vectorial optical VCSEL simulator based on modal expansion and coupled mode theory [8] is used to analyze the properties of the different cavity structures. The reliability of this approach has been verified in simulations of various VCSEL structures [9]–[11], showing good agreements with experimental results. The advantage of modal expansion approach over standard vectorial methods based on spatial grid such as finite element method (FEM) and finite-difference time-domain method (FDTD) is its higher speed with less memory requirement. For example, our modal expansion code takes a few seconds to 5 hours with 0.1 – 2 GB memory on a 3.0 GHz Core2Duo processor to find a mode, while FEM needs 10 – 30 hours with 20 – 50 GB memory on a 2.4 GHz Opteron processor [12].

The single mode property is characterized in terms of the mode stability factor S instead of the side-mode suppression-ratio (SMSR). The mode stability factor is a commonly used parameter in optical simulations of VCSELs; it is defined as:

$$S = (g_1 - g_0)/g_0 \times 100 (\%), \quad (1)$$

where g_0 and g_1 are the threshold material gains of the fundamental and first order modes, respectively. For reference, the surface relief VCSEL, a state-of-the-art single mode device, has S values of 55 – 85 % that typically correspond to a 30 dB SMSR, when its oxide aperture is 8 μm .

Hardley's effective index model is used only for calculating effective index profile [13].

3. Results and Discussion

All the simulation results are summarized in the Table 1.

3.1 Scattering Loss

Employing a dielectric PhC mirror instead of a semiconductor PhC mirror reduces the g_0 value by a half. This is because the smaller index difference of the dielectric mirror ($n = 2.29/1.48$) from the air hole ($n = 1$) than that of the semiconductor mirror ($n = 3.54/3.04$), results in a much smaller scattering loss. In the field intensity profiles of Fig. 2, much stronger scattered field is observed in the semiconductor PhC VCSEL case, both for the fundamental and first order modes.

In the dielectric VCSEL case, most of scattered field is emitted through the bottom DBR. The larger index contrast of the dielectric mirror ($\Delta n \sim 0.81$) results in high reflectivity that is less insensitive to the incident angles. This characteristic improves the beam quality of top emission, considerably.

3.2 Single-mode Strength

Using a dielectric PhC mirror drops also the S value. However, the S value of the dielectric PhC VCSEL, i.e. 57 % still can provide a stable single mode operation, as compared to the S value of the surface relief VCSEL which ranges from 55 to 85 %.

Table 1. Result Summary.

Measured quantity	Semi. PhC VCSEL	Diel. PhC VCSEL
Threshold gain, g_0	2403 (cm^{-1})	1224 (cm^{-1})
Stability factor, S	137 (%)	57 (%)
$1/e^2$ Mode size	5.02 (μm)	6.22 (μm)
$1/e^2$ Far-field angle	10.3 (degree)	11.0 (degree)

3.3 Mode Size & Far Field Angle

The mode size can be increased using the dielectric PhC. As shown in Fig. 3, the air holes of the semiconductor PhC leads to large effective index difference Δn_{eff} of 0.050, and the mode size is determined mainly by the air holes. But, in dielectric PhC VCSEL, Δn_{eff} due to air holes is 0.007 as small as Δn_{eff} due to oxide aperture. Thus, the mode size is determined both by air holes and by oxide aperture. Thus, the shallow index contrast in the dielectric PhC VCSEL structure can result in a larger mode size.

The larger mode size results in smaller far-field angle.

3.4 Single-Mode Output Power

Most importantly, the 50% larger modal area of the dielectric PhC VCSEL structure has the potential of considerably increasing the single-mode output power. The record value of single-mode output power from GaAs/AlGaAs QWs is 6 – 7 mW.

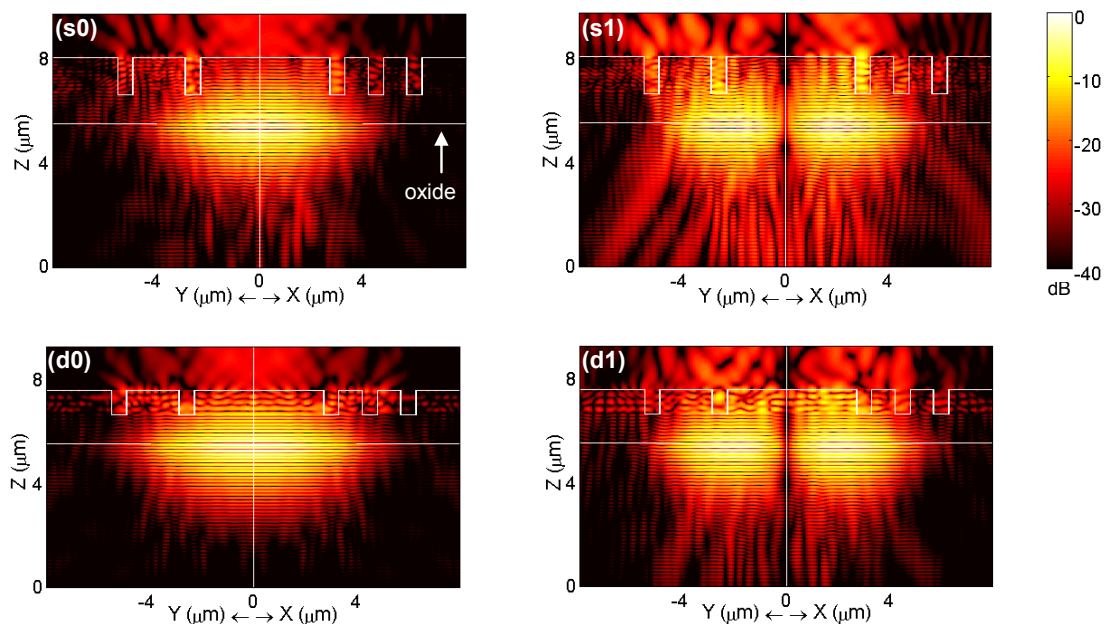


Figure 2. (*s0, s1*) X- and Y-cut cross-sectional intensity profiles of (*s0, s1*) fundamental and first order modes of semiconductor PhC VCSEL, and (*d0, d1*) those of dielectric PhC VCSEL. The intensity is normalized with respect to the peak intensity value at the active region, and is measured in dB scale.

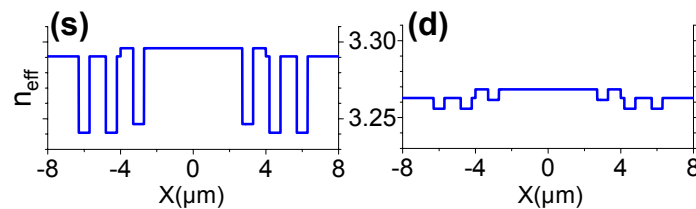


Figure 3. Effective index profiles of (*s*) semiconductor and (*d*) dielectric PhC VCSELs, obtained by effective index model [13].

4. CONCLUSIONS

A new high-power single-mode vertical-cavity surface-emitting laser structure employing a dielectric photonic crystal mirror has been suggested. Rigorous numerical investigations show that the new structure can have many good characteristics; small threshold gain, good beam quality, and high single-mode output power.

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